Water Quality Module Appendix

Background Discussion of Scientific Basis For Estimating the Effects of Watershed and Management Impacts on Water Temperature

Stream temperature has been widely studied and the physical processes controlling heat transfer are well understood. Most researchers have used an energy balance approach based on the physics of heat transfer to describe and predict changes in stream temperature. The six primary processes by which heat is transferred in aquatic environments are: 1) solar (short-wave) radiation, 2) radiation (long-wave) exchange with the sky and vegetation, 3) convection with the air, 4) evaporation, 5) conduction to the soil or streambed, and 6) advection from incoming water sources. Direct solar radiation is the primary source of energy for heating streams while reradiation of energy to the sky and vegetation and evaporation are the major sources of heat loss. Standing water undergoes the same heat transfer processes as streams. Most solar energy is absorbed in the upper 2 meters of water, depending upon opacity and other specific characteristics (Henderson-Sellers and Davies 1989). This portion of the water column is most subject to heating and cooling with solar radiation and heat exchange with the air. Thus all streams and wetlands and shallow lakes are affected by heat transfer processes described in this module.

The net energy balance, which is influenced by local environmental factors, determines the water temperature at a particular location at any particular time. Meteorological conditions averaged over the day explain daily maximum, mean, and minimum temperature (Edinger and Geyer, 1968). A thorough discussion of heat transfer mechanisms as they apply to forest streams can be found in Brown (1969), Theurer and others (1984), or Adams and Sullivan (1990).

Temperature of a waterbody seeks equilibrium with air temperature (Edinger et al., 1968) as both react to solar radiation with degree of adjustment primarily regulated by the local environmental factors of groundwater inflow, openness to the sky, relative humidity, and water depth (Adams and Sullivan, 1990). The combination of these factors at a site determines the energy balance and temperature.

Heat can be transported downstream with flowing water, although water temperature adjusts to local environmental conditions as it moves. If a stream flows from an open reach into a shaded reach, it will cool. Stream depth influences the rate of response (Brown 1969, Adams and Sullivan 1990, Sinokrot 1993). Very small, shallow streams respond rapidly, on the order of hundreds to a thousand feet. Deeper streams, including most fish-bearing streams, respond more slowly and the effect of the heating in the unshaded stream segment can be felt farther downstream, on the order of thousands of feet. When numerous less shaded reaches exist, there can be a downstream cumulative effect (Beschta and Taylor, 1988).

Table G-a1. Types of environmental variables affecting stream heating processes (from Sullivan et al. 1990).

GENERAL VARIABLE	EXAMPLE
GEOGRAPHY	latitude, longitude, elevation
CLIMATE	air temperature, relative humidy, wind velocity, cloudiness
STREAM CHANNEL CHARACTERISTICS	stream depth, width, velocity, substrate composition, water clarity
RIPARIAN OR TOPOGRAPHIC BLOCKING	sky-view (% shade), canopy density, vegetation height, crown radius, topographic angle

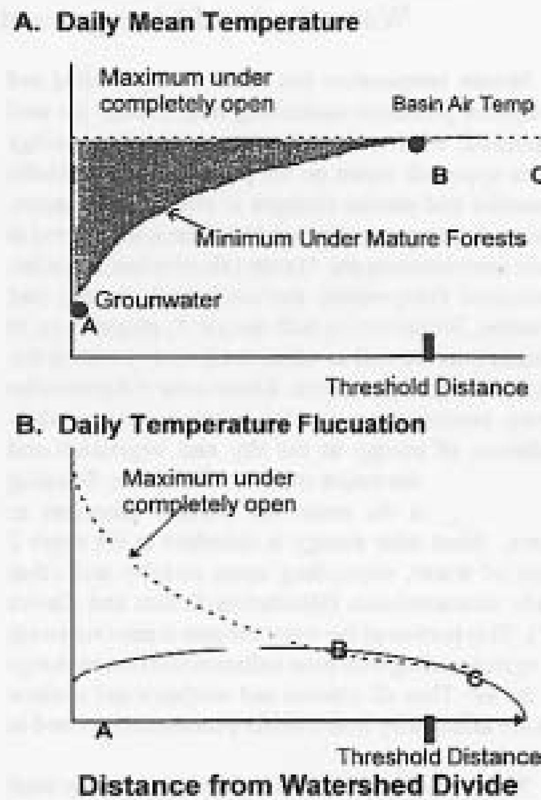
Temperature patterns within watersheds. Not all parameters are equally important for determining temperature regimes at all possible stream locations within the watershed. Rather, the relative importance of stream width, depth, shading, groundwater inflow, and air temperature in determing stream temperature tends to vary systematically by stream reach location within the watershed. Stream temperature tends to increase in the downstream direction from headwaters to lowlands, even under mature forest conditions. Expected stream temperature characteristics at a watershed scale are schematically presented in Figure G-a1 providing a conceptual framework for examining the interaction of these processes at both watershed- and stream reach-scales. This framework is thus helpful for understanding the use of reach-specific shade characteristics for estimating stream temperatureas described in this module.

Figure G-a1 depicts *daily mean* temperatures and *daily fluctuations* in stream temperatures. Note that the methods in this module estimate the effects of changes in riparian vegetation at a stream-reach scale on the *annual maximum* temperature expected for that stream reach. This time-scale was selected because it was the basis of the temperature/elevation screen (Sullivan et al. 1990), and because the stream temperature characterizations produced by this module can then be related to Washington's annual water temperature standard. In addition, estimates of the annual maximum temperature permit some interpretation about stream temperatures at other time intervals (e.g., if daily fluctuations in stream temperature increase, the annual maximum temperature would, by definition, also increase). Ongoing research and data collection on stream temperature processes is expected to produce additional methods to estimate stream temperature at other spatial scales and time intervals.

At the watershed scale, the curve A-C of the upper graph can be thought of as a probable longitudinal profile of daily average stream temperature for any given stream within the basin. That is, the curve describes, in a qualitative way, the expected increase in temperature as the stream flows from point A to C (Theurer et al, 1984). The expected temperature at point A is determined primarily by the combined effects of the riparian canopy in providing shading and the effect of groundwater inflow in depressing stream temperatures below the local daily air temperatures (Sullivan and Adams, 1989). For high elevation, or groundwater-dominated streams such as those close to source, the likely maximum summer temperature can be expected to vary from about 8-10 deg. C (Sullivan and Adams, 1990). This lower curve from point A to B thus traces a "reference" temperature profile that could be expected for streams under fully shaded mature forests. The shape of this baseline temperature would be expected to vary as a function of basin air temperatures, groundwater inflow, and differences in natural vegetation (Sullivan and Adams, 1990).

Point B on the upper schematic represents that point along the stream where mean stream temperatures equilibrate primarily to local air temperatures. This point is also referred to as the "threshold distance" (Sullivan et. a. 1990). In practice, this threshold distance is that distance from the stream's origin where water temperature is primarily determined by air tempature.

Figure G-a1. Conceptual diagram of increasing temperature with distance downstream from watershed divide.



This tends to occur where the average stream depth is approximately 0.6-1.0 meters and shade is not measureable. Upstream of this threshold distance (point B), riparian shading significantly affects stream temperature, and determines: (1) the degree to which average stream temperatures are depressed below local daily average air temperatures; and (2) the range of the daily fluctuations in stream temperature (i.e., maximum and minimum stream temperatures)(Sullivan and Adams, 1989, which Coweeta studies?). Similarly, the dashed upper curve shows the expected daily mean stream temperature expected for reaches upstream of this threshold depth. This daily average maximum temperature corresponds closely to average daily basin air temperature. The hachured area between the upper and lower curves represents the increases in daily mean stream temperature associated with varying degrees of riparian canopy removal.

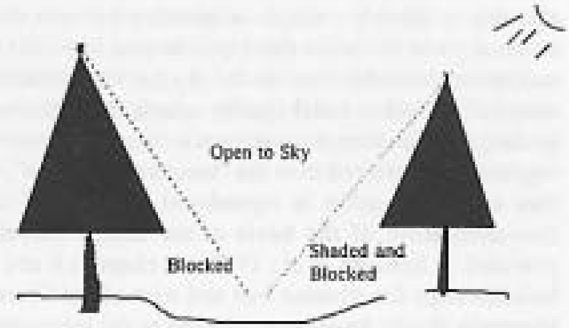
For the down-river point C, the maximum stream temperature is determined primarily by the basin air temperature. This is because low elevation, high-order streams tend to have: (1) relatively low contribution of groundwater to total streamflow; (2) stream widths that are too great for riparian vegetation to provide appreciable shading; and (3) stream depths sufficient to significantly dampen the daily stream response to solar heating (Theurer et al, 1984, Sullivan and Adams 1990). Stream temperatures that are raised above local air temperatures cool by reradiation, convection and evaporation processes, thus establishing a theoretical maximum stream temperature (Sullivan and Adams, 1990). Thus, at point C, the average stream temperature tends to equilibrate primarily to average air temperature.

The lower schematic portrays a similar longitudinal stream temperature profile from the perspective of daily fluctuations about the daily average temperature. For reaches upstream of the threshold distance, stream depth is a key parameter that determines how quickly the stream reach heats up, and how great the daily fluctuation in temperatures will be. As a general rule of thumb, the expected range in daily stream temperature fluctuations can be up to 75-80% of the daily fluctuation in local air temperatures (Sullivan and Adams 1990).

Assuming typical river valley formation, it appears that the portion of the watershed where vegetation has some effect on water temperature may lie within 50-60 km (31-37 miles) of the watershed divide in western Washington (Sullivan et al. 1990). Specific conditions within watersheds such as differences in valley form accompanying geologic substrate may alter the temperature profile and move the threshold for riparian vegetation influence up or downstream. Some valleys may be flatter or wider than average (e.g. glaciated terrain) and some may be steeper and deeper (e.g. incised or entrenched rivers). Elevation, vegetation, and summer air temperature differences may also make these relationships differ between watersheds east and west of the crest of the Cascade Mountains.

Determining shading effects of riparian vegetation. The waterbody's view-to-the-sky (the inverse of which is often inexactly referred to as "shade") (Adams and Sullivan, 1990) is a major environmental factor influencing stream temperature that can be affected by forest practices (Beschta et al. 1987). In the absense of riparian shade, water temperature will be near air temperature except where groundwater infow is significant. The proportion of the sky view that streamside vegetation can effectively block determines the proportion that water temperature will be depressed below air temperature.

Figure G-a2. Conceptual diagram of factors blocking radiation exchange and view-to-the sky.

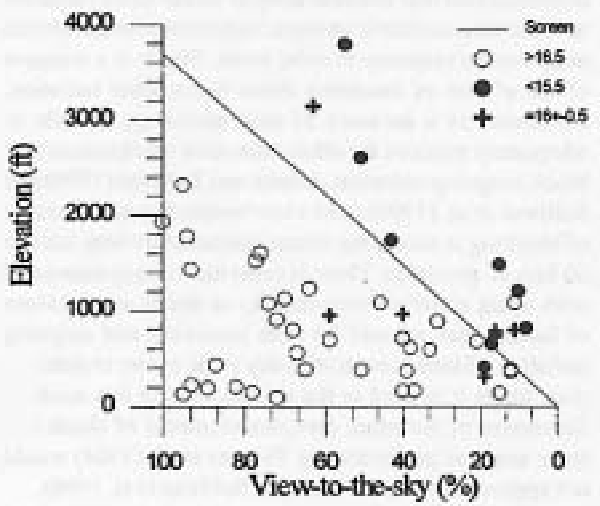


Blocking of in-coming and out-going radiation is determined by the height of streamside vegetation and topographic features within the overhead hemisphere that is the stream's "field of view" (Figure G-a2). The effect of blocking factors is very significant in small to moderate-sized forested streams, helping to maintain cool water temperature during warm summer months. Brown (1969) demonstrated that consideration of direct beam radiation to the stream surface is an important determinant of stream temperature response to solar input. Shade is a measure of the effects of incoming direct beam solar radiation. However, as a measure of heat exchange, it fails to adequately account for other important mechanisms that block outgoing radiation. Adams and Sullivan (1990) and Sullivan et al. (1990) used view-to-the-sky as a measure of blocking in modeling stream temperature with little or no loss of precision. There is some inaccuracy associated with using either view-to-the-sky or shade as a measure of factors that account for both incoming and outgoing radiation. Since view-to-the-sky is far easier to estimate than shade it is used in the calculations in this module. Treatment of the more complex elements of shade and solar angle as performed by Theurer et al. (1984) would not appreciably improve results (Sullivan et al. 1990).

The ability of vegetation to block incoming and outgoing radiation depends on its height relative to the width of the water body. Along very small streams almost any vegetation and streambanks themselves will provide shade, while tall trees and major topographic features are necessary for significant shading of larger rivers. Lakes are often too wide for any vegetation to be an effective control of water temperature. However, small or moderate-sized lakes may not be fully shaded but they may still be affected by the blocking of radiation by streamside vegetation. The maximum potential shade depends on the features of native vegetation.

View-to-the-sky and water temperature. An extensive study of temperature in Washington streams confirmed that watershed and landuse factors influenced water temperature consistent with previous research (Sullivan et al. 1990). Despite the complexities of site conditions on local control of temperature, the study was also able to identify a simple relationship between view-to-the-sky and elevation that could be used to predict the maximum allowable view-to-the-sky that would maintain temperature within water quality criteria for purposes of guiding riparian area management in state forest practice regulations. Referred to as the "temperature screen", the data and relationship is reproduced in Figure G-a3). Documentation of the basis of the simple model is provided in Sullivan et al., 1990, see chapters 6 and 7). Relationships for streams east and west of the Cascade Mountain divide have been adopted as the temperature screen by the Washington Forest Practices Board (WFPB, 1993) for use in prescribing shade requirements on a site-by-site basis.

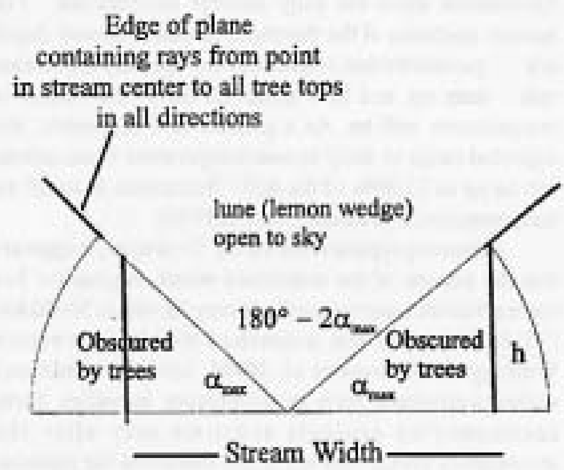
Figure G-a3. Temperature screen for westside plotted with original data from Sullivan et al. (1990). Included are 14 new data points from the Chehalis River.



Note that the screen isolates regions of the elevation/ view relationships where annual maximum temperature falls above or below 16.0oC. The line was fitted by eye to best envelope the data. When sites are misclassified, the screen tends to specify more shade than necessary (it misses more low temperature sites than high temperature sites). Only one data point on Figure G-a3 is warmer than expected given the elevation and view-to-the-sky of the site. At low elevations, considerable shade is required to maintain low temperature, and the definition of the boundary is more muted. When comparing measured versus modeled results, analysts are reminded that the screen is a first order approximation of temperature adopted on the basis of ease of use and reasonable accuracy for prescribing forest practices.

<u>Estimating view-to-the-sky based on vegetation.</u> Vulnerability to heat input is determined by evaluating potential temperature based on fully mature streamside forest conditions and likelihood that forest management can reduce shade sufficiently to exceed temperature standards. Since forest managment has altered many riparian forests from old growth forest conditions, there is rarely data available for measuring fully shaded stream conditions. This module provides a method for estimating the openness of the stream based on geometry of the riparian setting in the absence of measured data.

Figure G-a4. Definition sketch of view-to-the-sky in two dimensions.



Geometric relationships can be applied to calculate the angle from the stream center to the top of the blocking elements. In two dimensions, the sky can be represented as an arc of 180¡, and view-to-the-sky is the fraction of the arc that is unobstructed (Figure G-a4). Essentially this is in a vertical plane perpendicular to the stream banks. The larger the angle without obstructions, the larger view-to-the-sky. For a given maximum vegetation height (tree or shrub as appropriate) and stream width, it is possible to calculate view-to-the-sky as the portion of the horizon not blocked by vegetation and topography.

(Figure G-a5). If the angle α is greater than the hillslope angle (λ), then the stream does not "see" trees beyond the first solid block of trees near the bank and α is the appropriate angle for estimating view-to-the-sky and the effects of topography can be ignored. If the nearstream angle is less than the hillslope angle, than the sideslopes provide more blocking than the streamside trees and topographic effects are significant. In this case, the hillslope angle λ is the appropriate angle to use for the calculations. Topography may be a significant factor reducing view-to-the-sky along stream segments that are moderately to tightly constrained.

Stream width affects view-to-the-sky by determining the location of the closest vegetation to the stream center, and thus the angle and proportion of the overhead hemisphere blocked (Figure G-a6). Small streams can be nearly completely shaded by overhanging trees or shrubs. Medium streams can be partially shaded by trees of suitable size. The largest streams get little shade from even the tallest trees. It should be noted that the view-to-the-sky is not dependent on the angle of the sun, which will vary during the year and with latitude. Using view-to-the-sky as the measure rather than shade allows estimates based on riparian geometry.

This 2-dimensional representation over-simplifies the surface area of the 3-dimensional hemisphere above the stream. View-to-the-sky is the fraction of a hemisphere centered over the stream which is unobstructed by vegetation or topography (Figure G-a7). The hemisphere extends from horizontal to vertical (0-90¡ of elevation), and around the compass (0-360¡ of azimuth). View-to-the-sky is therefore a 3 dimensional concept. There is an occluded plane that contains the line along the center of the corridor and the line formed by the top of the trees. The intersection of this plane and the celestial sphere is a great circle. The horizontal plane at the stream surface also intersects the celestial sphere forming a hemisphere which is the potential field of view of the water surface.

Topography can also affect the view-to-the sky Similarly, the same size tree can have very different effect on the view-to-the-sky depending on the stream width. Only on a perfectly flat landscape with no vegetation or topography is it possible to attain a view-to-the-sky of 100%.

Figure G-a5. Effects of stream width on view-to-the-sky.

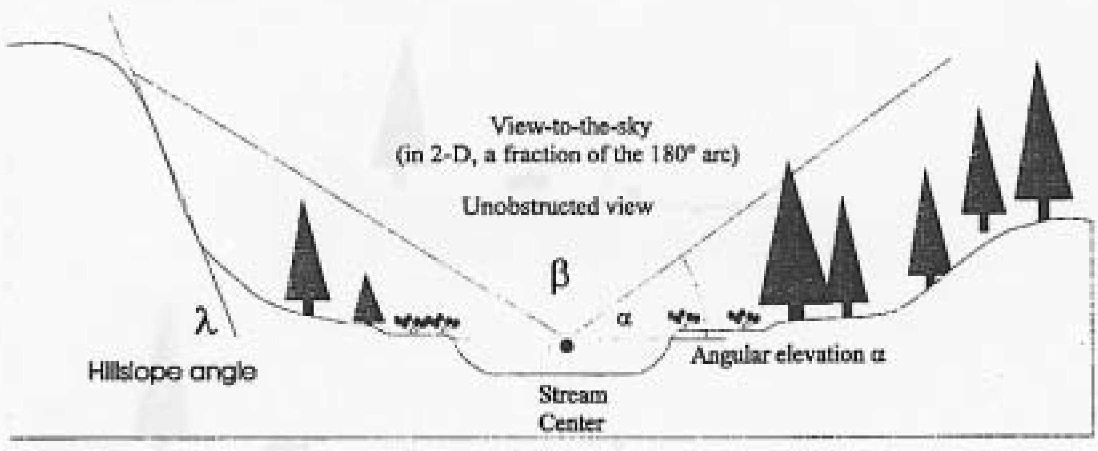
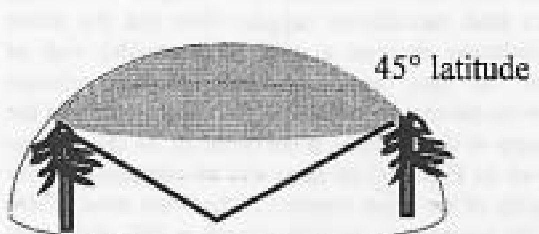


Figure G-a6. Effects of stream width on view-to-the-sky.

Figure G-a7. Three-dimensional representation of the sphere of view of a waterbody.



Consider the hemisphere in quadrants (Figure G-a8). On wider streams, quadrants facing the banks may have a considerable portion of the angular view blocked by vegetation, while quadrants facing up and downstream may be quite open. This geometry can have an important effect on estimations of view-to-the-sky in wider channels. The slice of sky viewed by the stream between two banks of trees is represented as the area of a geometric shaped termed a "lune" defined by the angle α (degrees) on a celestial sphere (Figure G-a4). To calculate view-to-the-sky, first determine the angle, α (in degrees) that is open above the stream (Figure G-a4). The angle α may be directly measured, or estimated from equation 1 based on the height of trees (h) and width of stream (w).

$$\alpha = \mathrm{ArcCos}\,(w/\ \mathrm{SQRT}\,(w^2+4h^2)) \qquad (1)$$

The surface area (A) for the lune whose angle is α is:

$$A = (180-2\alpha/360)4\pi r^2 \qquad (2)$$

$$= 2\pi r^2 - \frac{\pi r^2 \alpha}{45} \qquad (3)$$

The calculation of view-to-the-sky involves dividing the surface area of the lune above the stream by the surface area of the entire horizon above the stream plane.

$$\text{View-to-the-sky (\%)} = \frac{(2\pi r^2 - \pi r^2 \alpha/45)100}{2\pi r^2} \qquad (4)$$

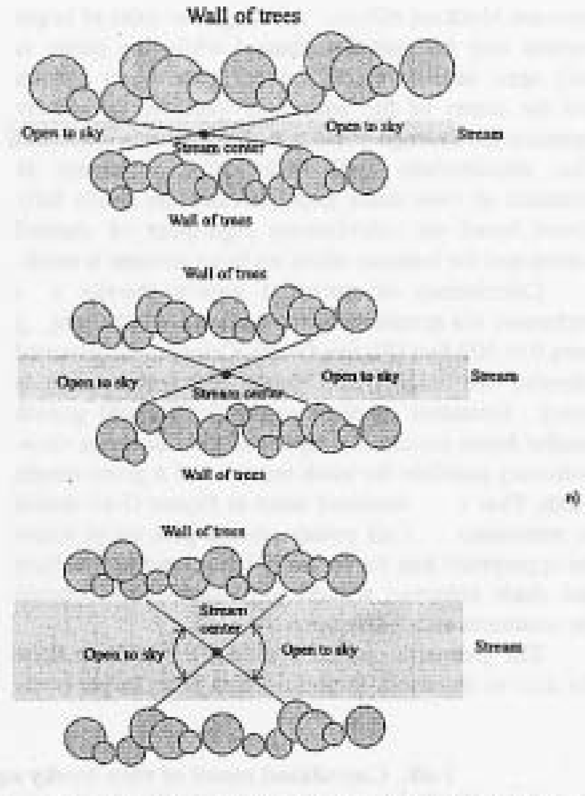


Figure G-a8 Conceptual diagram of the three-dimensional view-to-the-sky from the center of a straight reach of stream

Considering the horizon of view, and therefore r, as large, the radius cancels from the equation with division, making the area of the lune primarily dependent on the angle formed by the trees. This simplifies to

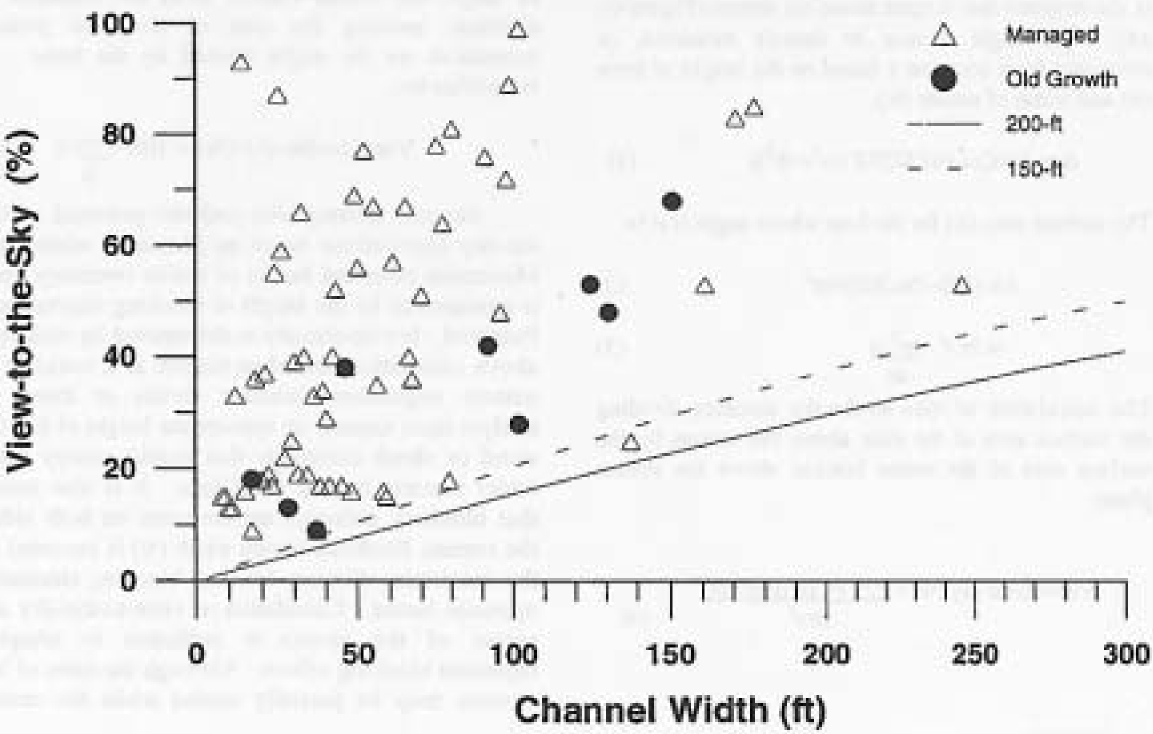
$$\text{View-to-the-sky (\%)} = 100 - \frac{10}{9}\alpha \qquad (5)$$

Several assumptions underlie potential view-to-the-sky calculations based on geometric relationships. Maximum potential height of native overstory species is assumed to be the height of blocking vegetation (h). Potential view-to-the-sky is determined by making the above calculations based on the site as it could be with mature vegetation (whether shrubs or trees). The analyst must assume an appropriate height of the forest stand or shrub commuity that would occupy the site under historic natural conditions. It is also assumed that blocking elements are the same on both sides of the stream. Bankfull stream width (w) is assumed to be the maximum distance between blocking elements on opposite banks. Calculation of view-to-the-sky at the center of the stream is sufficient to adequately represent blocking effects. Although the sides of larger streams may be partially shaded while the center is represent blocking effects. Although the sides of larger streams may be partially shaded while the center is fully open, heat is rapidly mixed in the water column and the center of the stream is likely to adequately represent the average condition. Streams may meander. This characteristic will make little difference in estimates of view since small streams are nearly fully closed based on calculations regardless of channel pattern and the horizon effect on large streams is small.

Calculations of potential view-to-the-sky were performed via spreadsheet for bankfull widths ranging from 0 to 300 feet (Figure G-a9). Calculations assumed effective tree heights of 150 and 200 feet (shown as lines). Estimates of view-to-the-sky for old growth conifer forest conditions represent the minimum view-to-the-sky possible for each segment of a given stream width. Thus the calculated lines in Figure G-a9 should be minimums and all points should plot on or above the appropriate line for forest height. Streams that have had shade removed should plot somewhere between the minimum and 100% open.

The geometric model provides a minimum fit to the data as expected, including data from larger rivers (Figure G-a9). Although the maximum height modeled was 200-feet, view-to-the-sky in old growth forests appeared to have a best fit by assuming tree height of 150-feet or less, although trees in old growth or mature forest stands were undoubtedly taller than this. There may be several reasons why streams appear to be more open than calculations suggest. Note that the above formulation assumes a solid (impenetrable) wall of trees. In fact, real trees only partially obscure view-to-the-sky, especially in the upper portion of the canopy or if vegetation is not dense. In the calculations shown in Figure G-a9 there was no compensation for opacity of the upper portions of the forest stand. These results suggest that perhaps as much as 25% of the total tree height has a significant loss of opacity which was not accounted for in calculations. Thus, view-to-the-sky calculations using total tree height bias estimates of minimum view to lower values than probably naturally occur. It also appears that 150-ft or 75% total tree height is a better estimator of the blocking effect of mature conifers on the westside of the Cascades.

Figure G-a9. Calculated result of view-to-sky equations for effective height equal to 200-ft and 150-ft. Data from TFW sources for westside sites is also plotted tocompare to the vegetation calculations. Points labeled "managed" were collected by TFW cooperators along streams with various histories of logging in riparian areas. Sites labeled "Old Growth" were reported to be representative of old growth stand conditions. Lines are labeled according to tree height used in the calculation.

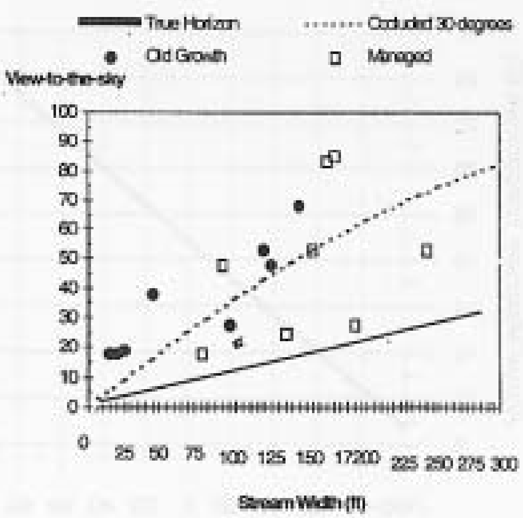


Conversely, the densiometer measuring instrument overestimates the openness of the stream. The convex mirror of the instrument is inset into the wood platform on which it is mounted. The emplacement of the mirror into the platform occludes nearly 30 degrees at the base of the mirror, thus seeing less of the horizon at the base than the stream would "see". Although an apparently small amount when gazing at the instrument, this portion represents a rather large area of the hemisphere above the stream. As much as 50% of the area of a hemisphere lies below 30 degrees on the horizon which would not be measured with the instrument. The larger the stream, the greater the effect on measured view.

However, overestimation of openness during measurement partially accounts for real differences in effectiveness of energy transfer around the celestial sphere. Energy exchange is not equal around the hemisphere: it reaches a maximum straight overhead and declines toward the horizon with the cosine of the angle according to Lambert's Law (Mills, 1992).

Algebraically solving for this factor in the above calculations for the lune illustrates the instrument bias (Figure G-a10). Note that the measured view of larger channels is more open to the sky than predicted by the equations (Figure G-a9). For larger streams, the calculated view appears to be more representative of the true condition, and is reasonably consistent with most observations. In reality, the effective view-to-the-sky lies somewhere between that calculated using equation 4 and that measured in the field by a spherical densiometer. This analysis uses the calcuated view recognizing that it underestimates the actual view-to-the-sky.

Figure G-a10. Calculated view -to-the-sky of 150-ft tall trees assuming horizon at the ground, and horizon at 30 degrees above the ground as measured by spherical densiometers. Also shown are data from Figure G-9 representing old growth sites and other sites with stream widths greater than 100 feet.



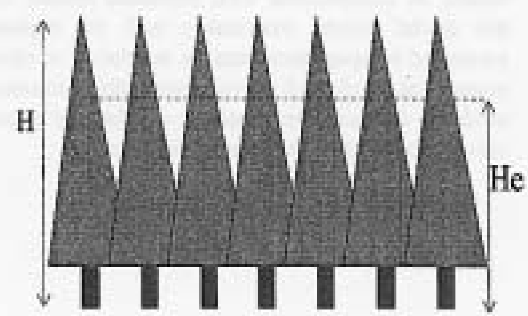
The stream's view of the hemisphere of the sky above it depends on the height and light filtering capacity of objects blocking that view. View-to-the-sky is therefore a function not only of the width of the stream but also of factors that control the height and density (Figure G-a11). To compensate for the gaps in vegetation cover, as viewed sideways from the stream, the analyst can take several steps which further improve the calculation. Since most trees are full in the mid-canopy, but less than opaque in the tree-tops, the analyst can translate that partial opacity into an effective tree height.

$$H_E = H * \% \text{ opacity} \qquad (6)$$

A 120-foot Douglas-fir might be 70% opaque. The effective tree height would then be 84 feet

View-to-the-sky can be calculated by the same formula given above, but substituting effective tree height H_e for H. An additional correction may be needed if the trees are sparse, for example in east-side situations where there are substantial gaps between trees. Use of an opacity factor should be based on field estimates from reference sites and should be ignored if these are not available.

Figure G-a11. Conceptual view of opacity factor accounting for openness of stand.



He = effective tree height
H = total tree height

Estimated temperature based on view-to-the-sky. Data on which the temperature screen was developed from the TFW temperature study (Sullivan et. al. 1991) was used to develop a relationship between view-to-the-sky and maximum temperature. In Figure G-a3, the line representing the temperature screen approximates the relationship between elevation and view-to-the-sky where water temperature is equal to 16°C. Conceptually, the distance each point is away from the line for a given elevation should reflect the distance temperature is likely to vary from the reference. Thus, the difference between existing or potential view-to-the-sky and the screen reference view-to-the-sky can be translated to water temperature as shown in Figure G-a12.

The TFW temperature study provided a rule of thumb estimate that 10% change in view-to-the-sky results in 0.6°C (1°F). Analysis of Figure G-a12 allows recalibration of this relationship to 0.7 °C (1.3°F). The relationship plotted in Figure G-a12 was reformatted for ease of use in water quality module calculations in Figure G-a13.

This approach to calculating maximum temperature has better predictive capability than linear regression of view-to-the-sky and temperature (R^2=.34). The method can be easily applied at the watershed scale using potential or existing view-to-the-sky. The analysis should provide a generalized perspective of temperature at that scale, although it is probably imprecise in locating exact temperature profiles.

Results suggest that this simple approach to estimating water temperature should provide a first approximatation of annual maximum temperature at the watershed scale. There is scatter in the relationship (Figure G-a12) and the water quality analyst should use care in interpreting modeled results in comparison with measured results. Since the model works reasonably well for explaining measured temperature patterns in relation to riparian vegetation, it should provide reasonable estimates of modeled temperature based on estimates of potential view calculated from riparian geometry.

Figure G-a12. Annual maximum temperature in relation to the Difference in view-to-the-sky between potential and allowable based on the temperature screen.

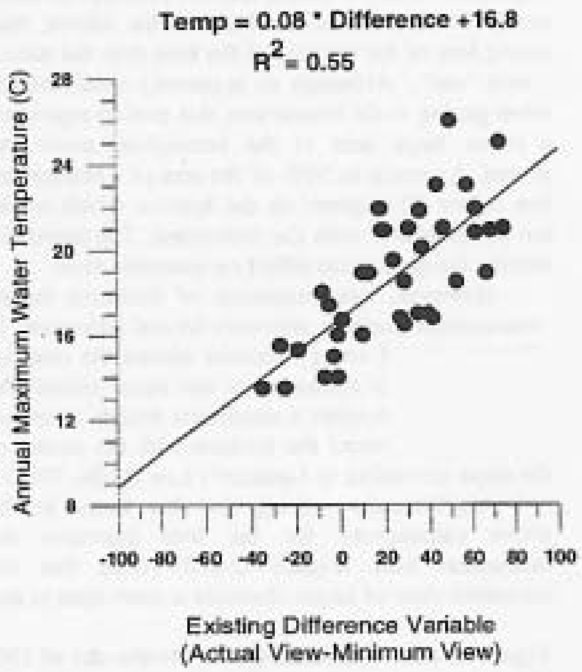


Figure G-a13. Simple model for predicting annual maximum temperature in western Washington based on view-to-the-sky and elevation.